

# High-energy cosmic ray production by a neutron star falling into a black hole

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We propose a one-shot mechanism for high-energy cosmic ray generation by a neutron star falling into a black hole surrounded by low density plasma. The function of the black hole in this scenario is to accelerate the star to a speed *arbitrarily* close to that of light. When the star — essentially, a magnetized sphere — approaches the horizon it imparts energy to the ambient plasma charges via the induced electric field. Disregarding radiation losses, for iron nucleus, a simple estimate gives energies on the order of  $10^{19}$  eV for stars with magnetic fields as weak as  $10^6$  teslas. The proposed mechanism should also work in chance encounters between rapidly moving neutron stars and molecular clouds. The rarity of such encounters may explain the apparent randomness and rarity of the high-energy cosmic ray events.

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The origin of high- and ultra-high-energy (HE and UHE, respectively) cosmic rays — charged nuclei with energies up to and exceeding  $10^{18}$  eV arriving to Earth from outer space — has been the subject of numerous discussions for more than fifty years [1–4]. Several mechanisms explaining the acceleration process have been put forward [5], chief among them being diffusive shock acceleration based on the Fermi mechanism [6], and one-shot acceleration in a strong electric field induced by a rapidly rotating pulsar [7]. Here we propose another one-shot mechanism to accelerate charges to ultra-high energies.

Envision a magnetized neutron star on a collision course with a black hole surrounded by a low density plasma. An observer hovering above the horizon suddenly sees the star rapidly flying by. The changing magnetic field  $B$  at the observer’s location induces an electric field that accelerates the particles of the surrounding plasma. Acceleration of a given charge lasts for only a brief time,  $\Delta t \simeq R/v$ , where  $R$  is the radius of the neutron star and  $v$  is its speed relative to the hovering observer, which near the horizon approaches the speed of light,  $c$ . The work  $W_q$  done by the induced electric field  $E$  on a charge  $q$  is then, roughly,

$$W_q \simeq qEc\Delta t \simeq qER \simeq q\frac{\Delta B}{\Delta t}R^2, \quad (1)$$

where in the application of Faraday’s law we have chosen an Amperian loop in the form of a circle of radius  $R$ . Taking  $\Delta B \simeq B$ , we get an estimate

$$W_q \simeq qBRc. \quad (2)$$

For iron, with  $q = 26 \times 1.6 \times 10^{-19}$  C, and the star with  $R \simeq 5 \times 10^3$  m, even for a relatively weak magnetic field of  $B \simeq 10^6$  T, this gives particle energies on the order of  $W_q \simeq 1 \text{ J} \simeq 10^{19}$  eV. This estimate agrees with the Hillas criterion for one-shot cosmic ray production [8]; it also follows from dimensional analysis: Eq. (2) is the simplest reasonable combination of quantities playing a role in this scenario that has units of energy.

Like any other induction-based one-shot acceleration scenario, our mechanism suffers from the limitations imposed by radiation losses [9–11]. For the iron nucleus, the maximum attainable energy in the synchrotron-loss-saturated regime under the conditions quoted above is given by

$$\mathcal{E}_{\text{syn}} = \sqrt{\frac{3}{2} \frac{4\pi\epsilon_0 (mc^2)^4}{q^3 c B}} \simeq 10^{16} \text{ eV}, \quad (3)$$

where  $\epsilon_0$  is the permittivity of free space, and  $m$  is the mass of the nucleus [9]. However, since UHE cosmic ray production is ultimately a quantum mechanical process, its probabilistic nature may allow the occurrence of rare events at energies much higher than  $\mathcal{E}_{\text{syn}}$ . Additionally, there may also be a possibility of a purely kinematical resolution of the above mentioned limit.

Thus, disregarding the radiation constraint, let us take a closer look at the proposed acceleration mechanism by performing a quantitative analysis of particle motion in the field of a rapidly approaching magnetic dipole. The process is schematically shown in Fig. 1. The star is modeled as a magnetized sphere whose dipole moment  $\mathbf{M}$  is assumed to be perpendicular to the direction of its propagation. In the frame of the star, the charge is seen as impinging on the magnetic dipole at ultra-relativistic speed,  $v \simeq c$ . The sideways kick it receives due to the Lorentz force  $q\mathbf{v} \times \mathbf{B}$  is the proposed mechanism for the cosmic ray production.

A curious conceptual analogy is in order here. The problem of the motion of charges in the field of a magnetic dipole has a long history and is known as the Störmer Problem [12, 13]. It forms the basis of the theory of polar auroras in Earth’s atmosphere [14]. It is used to explain the mechanism by which the incoming cosmic rays get trapped by the magnetic field of the Earth. Our scenario then is the opposite of the aurora (call it “anti-aurora”) — the charges, instead of being trapped, get scattered away from the dipole.

In cylindrical coordinates, the Lagrangian  $L$  of a particle with mass  $m$  and charge  $q$  moving with speed  $v$  in

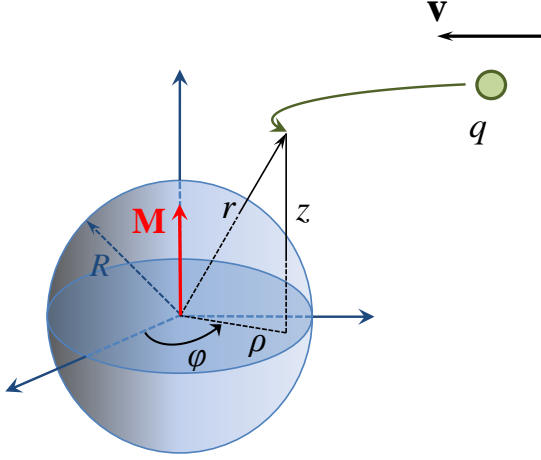


FIG. 1: (color online). Schematic representation of motion of a charged particle  $q$  as viewed from the reference frame of the neutron star (depicted here as a magnetized sphere of radius  $R$  having the magnetic dipole moment  $\mathbf{M}$ ). The black hole horizon is shown in black. The sideways kick received by the charge during the encounter is the mechanism behind the ultra-high-energy cosmic ray production. Gravitational forces acting on the charge during this encounter are ignored.

the magnetic field of the dipole  $\mathbf{M} = M\hat{\mathbf{z}}$  is given by

$$L = -mc^2 \sqrt{1 - \frac{v^2}{c^2}} + \frac{\mu_0}{4\pi} \frac{qM\rho^2\dot{\varphi}}{(\rho^2 + z^2)^{3/2}}, \quad (4)$$

where  $\mu_0$  is the permeability of free space, and the over-dot indicates differentiation with respect to time  $t$ . There are two constants of motion in this problem: the speed,

$$v^2 = \dot{\rho}^2 + \rho^2\dot{\varphi}^2 + \dot{z}^2, \quad (5)$$

and the generalized momentum,

$$p_\varphi = \gamma m \rho^2 \dot{\varphi} + \frac{\mu_0}{4\pi} \frac{qM\rho^2}{(\rho^2 + z^2)^{3/2}}, \quad \gamma \equiv [1 - v^2/c^2]^{-1/2}, \quad (6)$$

which at large distance has the meaning of the usual angular momentum with respect to the  $z$  axis. In the so-called “equatorial limit” (corresponding to the initial conditions  $z(0) = 0$ ,  $\dot{z}(0) = 0$ , which lead to  $z(t) = 0$  for all  $t$ ), particle motion in the radial direction is described by the effective Lagrangian

$$L_{\text{eff}} = \frac{1}{2} \gamma m \dot{\rho}^2 - \frac{1}{2\gamma m \rho^2} \left( p_\varphi - \frac{\mu_0}{4\pi} \frac{qM}{\rho} \right)^2. \quad (7)$$

From this, for a head-on collision with  $p_\varphi = 0$ , we can find the point of closest approach,

$$\rho_{\min} = \sqrt{\frac{\mu_0}{4\pi} \frac{qM}{\gamma m v}}. \quad (8)$$

If we now take into account the relation between the dipole moment  $M$  of the sphere and the magnetic field  $B_0$  on the equator,

$$M = \frac{4\pi}{\mu_0} B_0 R^3, \quad (9)$$

and use

$$\gamma m v = \sqrt{\frac{\mathcal{E}^2}{c^2} - m^2 c^2}, \quad (10)$$

then by setting

$$\rho_{\min} = R \quad (11)$$

we can determine the upper energy,  $\mathcal{E}_{\max}$ , relative to the neutron star at which the particle can still be deflected by the star’s magnetic field. Substitution of Eqs. (10) and (9) into Eq. (8) gives

$$\mathcal{E}_{\max} = c \sqrt{q^2 B_0^2 R^2 + m^2 c^2}, \quad (12)$$

in agreement with the previous estimate. We still need to find the deflection angle,  $\Delta\varphi$ , however, since it is this angle that provides information about the energy transfer in the original reference frame of the observer.

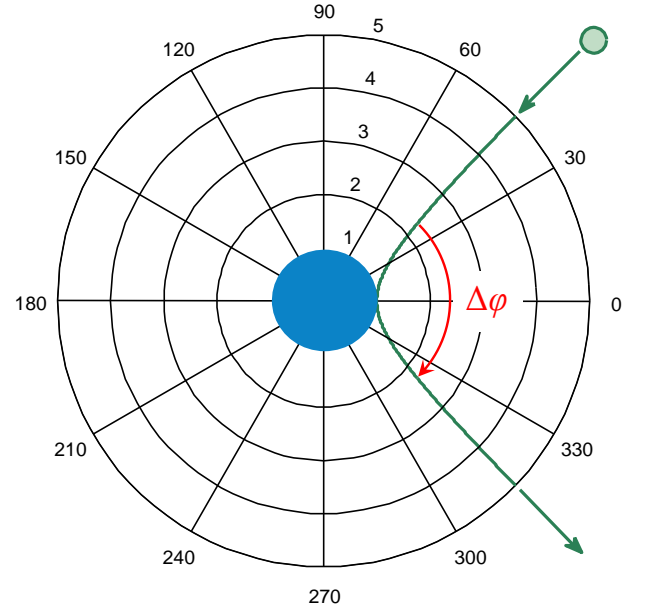


FIG. 2: (color online). Trajectory of a charged particle (shown in green) with energy  $\mathcal{E}_{\max}$  during a head-on collision with a neutron star (shown in blue), as seen from the moving frame of the star. All distances are measured in units of  $\rho_{\min}$ , the angles are given in degrees.

To find  $\Delta\varphi$  for a head-on collision, we write the conservation equations (5) and (6) in the dimensionless form,

$$\left( \frac{dx}{d\tau} \right)^2 + x^2 \left( \frac{d\varphi}{d\tau} \right)^2 = 1, \quad (13)$$

$$x^2 \frac{d\varphi}{d\tau} + \frac{1}{x} = 0, \quad (14)$$

with  $x \equiv \rho/\rho_{\min}$ ,  $d\tau \equiv (vdt)/\rho_{\min}$ . From Eq. (14) we get  $d\tau = -x^3 d\varphi$ , which upon substitution into Eq. (13) leads to the trajectory equation,

$$\frac{d\varphi}{dx} = \pm \frac{1}{x\sqrt{x^4 - 1}}, \quad (15)$$

whose solution is

$$\varphi - \varphi_0 = \pm \frac{1}{2} \arctan \left( \sqrt{x^4 - 1} \right). \quad (16)$$

The corresponding trajectory at  $\mathcal{E}_{\max}$  is depicted in Fig. 2. Notice that the deflection angle in this head-on collision is  $\Delta\varphi = \pi/2$ , which means that in the original frame of the observer the angle is

$$\Delta\varphi_{\text{obs}} = \arctan \left( \frac{mc^2}{\mathcal{E}_{\max}} \right) \ll 1, \quad (17)$$

and the particle will be seen as having energy

$$\mathcal{E}_{\text{obs}} = \frac{\mathcal{E}_{\max}^2}{mc^2} \gg \mathcal{E}_{\max} \gg mc^2. \quad (18)$$

The direction in which the particle will be flying away from the impact site will depend on the exact kinematics

of the collision. In the case of a neutron star radially falling into a Schwarzschild black hole, the particle initially present near the black hole will be pushed towards the singularity. In a more interesting case corresponding to the neutron star slowly spiraling into the black hole, the particle may be ejected along a (near) tangential trajectory. A variation of the latter case may involve the Banados-Silk-West mechanism [15–18], in which both the neutron star and the charge are falling into a Kerr black hole from opposite directions.

The above quantitative analysis thus provides justification for our main assertion: that direct collisions between neutron stars and black holes may lead to the production of HE cosmic rays. The attractive features of this mechanism include: (i) its conceptual simplicity, (ii) its applicability to black holes of wide range of sizes (not just supermassive), (iii) the relatively weak magnetic fields involved, and (iv) the possibility of cosmic ray generation in chance encounters between rapidly moving neutron stars and molecular clouds. The rarity of the high-energy cosmic ray events is seen as a consequence of the accidental nature of all such collisions.

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